IoT-Enabled Autonomous Fire Detection and Extinguishing System Using Arduino

Dr. A. Nagesh,
Professor, IT Department,
Mahatma Gandhi Institute of Technology, Hyderabad, Telangana

Dendukuri Naga Vaishnavi
Department of IT
Mahatma Gandhi Institute of Technology
Hyderabad, Telangana

Department of IT
Mahatma Gandhi Institute of Technology
Hyderabad, Telangana

Eshaboina Aravind

Abstract: **This project is developed in the domain of Internet of Things (IoT) for intelligent fire safety systems, aiming to provide a reliable solution for early detection and rapid suppression of fire hazards. Fire accidents are unpredictable and can cause severe damage, making automated and connected safety systems essential. To address this, an IoT-enabled Arduino-based autonomous fire detection and extinguishing system is designed, which uses flame sensors, smoke sensors, and embedded control algorithms to continuously monitor the environment. Upon detecting fire, the Arduino microcontroller processes real-time sensor data, identifies the fire location, and autonomously navigates toward the source using a motor driver-controlled robotic system. Once the fire source is reached, an actuation mechanism consisting of a water pump and nozzle system is activated to suppress the flames efficiently, along with optional audio alert modules for immediate warning. Through IoT integration, the system supports remote monitoring and real-time communication, enhancing safety and control. After extinguishing the fire, the system resets to its monitoring state, ensuring continuous operation. By integrating sensor-based detection, autonomous navigation, and IoT connectivity, this project offers a low-cost, efficient, and scalable solution suitable for households, laboratories, warehouses, and small-scale industries, highlighting the importance of smart embedded systems in modern fire safety management.**

Keywords: Fire detection, Fire suppression, Arduino, Autonomous system, Hazard management, Microcontroller-based automation, Safety.

I. INTRODUCTION

Fire accidents are a major threat to life and property in homes, industries, and public places. Early detection and quick response are essential to reduce damage.

Traditional fire-fighting methods involve human intervention, which can be dangerous due to heat, smoke, and toxic gases.

With the advancement of embedded systems and robotics, automated solutions can be developed to handle fire accidents safely. A fire-fighting robot is an intelligent system that can detect fire and extinguish it without human involvement.

The proposed system uses Arduino Uno as the main controller. Sensors such as flame sensor and smoke sensor are used to detect fire conditions. These sensors continuously monitor the environment and send signals to the Arduino when fire is detected.

Based on sensor input, the Arduino controls the movement of the robot using DC motors and motor driver module. The robot moves toward the fire source and activates a water pump/fire extinguisher system to put out the fire. Additionally, the system can be enhanced with a voice alert or buzzer module, which provides an audio warning when fire is detected, improving safety and awareness.

This project demonstrates a low-cost, efficient, and automated fire safety system using robotics. It can be used in areas where human access is risky, such as industries, warehouses, and laboratories.

In practical fire detection systems, achieving high sensitivity while minimizing false alarms is a critical challenge. Flame sensors are highly responsive to infrared radiation emitted by fire but may also react to strong ambient light sources. On the other hand, smoke sensors provide additional confirmation but introduce a slight delay in detection. Therefore, combining multiple sensors using a sensor fusion approach improves reliability and robustness. Furthermore, integrating autonomous navigation enables the system to respond without human intervention, making it suitable for hazardous environments.

Despite the availability of fire detection systems, many existing solutions either rely on manual intervention or lack integration of autonomous navigation and real-time response. Additionally, limited emphasis has been placed on quantitative performance evaluation of such systems. The objective of this work is to design and develop a low-cost, IoT-enabled autonomous fire detection and extinguishing system that not only detects fire accurately but also responds efficiently

through robotic navigation and automated suppression, while evaluating system performance using measurable metrics such as accuracy, precision, and response time.

II. RELATED WORK

The development of fire detection and fire-fighting systems has gained significant attention with the advancement of embedded systems, robotics, and IoT technologies**.** Many researchers have proposed automated systems to reduce human risk and improve response time during fire accidents. These systems mainly focus on early fire detection, autonomous navigation, and alert mechanisms. However, the level of automation, cost, and efficiency varies across different approaches.

Sensor-Based Fire Detection Systems

Many fire detection systems use flame sensors and smoke sensors to identify fire at an early stage. These systems are simple, cost-effective, and suitable for small-scale applications. However, they lack automation and require manual intervention for fire suppression.

Arduino-Based Fire Fighting Robots

Several projects have been developed using Arduino microcontrollers and motor driver modules to create fire-fighting robots. These systems can detect fire and move toward the source using DC motors. While they provide automation, most of them have limited features and basic functionality.

IoT-Based Fire Safety Systems

Recent research focuses on IoT-enabled fire detection systems, where sensor data is transmitted to cloud platforms for real-time monitoring and alerts. These systems improve response time and allow remote control, but they depend on stable internet connectivity and can increase system complexity.

Alert and Communication Systems

Some systems integrate buzzer alerts, GSM modules, and voice-based notification system**s** to inform users when fire is detected. These features improve safety by providing immediate warnings and enabling quick action.

Limitations of Existing Systems

Although existing systems provide fire detection and basic automation, many lack integration of autonomous navigation, real-time alerts, and cost efficiency in a single system. This creates the need for a combined solution that is both effective and affordable.

Proposed System Contribution

The proposed system integrates sensor-based detection, Arduino control, robotic movement, and optional IoT and voice alert modules into a single platform. This makes the system efficient, low-cost, and suitable for practical applications.

III. METHODS AND MATERIALS

The proposed fire-fighting robot system is designed to provide an automated solution for fire detection and suppression by integrating **sensors, embedded systems, and robotic mechanisms**. The system continuously monitors the environment, detects fire using sensors, processes the data using a microcontroller, and performs necessary actions such as movement and fire extinguishing. The overall system consists of multiple components working together to achieve reliable and efficient operation.

Hardware Components

The system includes components such as Arduino Uno, flame sensor, smoke sensor, motor driver (L298N), DC motors, water pump, battery, and robot chassis. These components are interconnected to form a complete robotic system capable of detecting and extinguishing fire.

Fire Detection Mechanism

The fire detection system uses flame and smoke sensors to monitor the surroundings. The flame sensor detects infrared radiation emitted by fire, while the smoke sensor identifies the presence of smoke particles. When fire is detected, the sensors send signals to the Arduino for further processing.

Threshold Selection and Calibration:

The fire detection threshold was determined experimentally by observing sensor readings under normal and fire conditions. The average ambient sensor value ranged between 10–15, while fire conditions produced readings between 30–80. Therefore, the threshold value was selected using:

$$\text{Threshold} = (\text{Ambient} + \text{Fire}) / 2 = (15 + 30) / 2 = 22.5 \approx 25$$

This threshold ensures reliable detection while minimizing false positives caused by environmental noise.

Control Unit (Arduino Processing)

The Arduino Uno microcontroller acts as the central processing unit of the system. It receives input signals from the sensors and processes them using programmed logic. Based on the sensor data, the Arduino controls the movement of the robot and activates the extinguishing system.

Robot Navigation System

The robot moves using DC motors controlled by a motor driver module (L298N). The motor driver acts as an interface between the Arduino and motors, enabling the robot to move forward, backward, and turn toward the fire source.

The robot uses a differential drive mechanism, where two DC motors are independently controlled to achieve forward motion and directional changes. The motor driver (L298N) acts as an interface between the Arduino and motors, enabling precise control of speed and direction.

By varying the logic signals sent to the motor driver, the robot can move forward, stop, or adjust direction toward the detected fire source.

Fire Extinguishing Mechanism

Once the robot reaches the fire source, a water pump system is activated. The pump sprays water through a nozzle to extinguish the fire. This mechanism ensures quick and effective suppression of flames.

Alert and Communication Module

The system can be integrated with a buzzer or voice module to provide an alert when fire is detected. This enhances safety by notifying users immediately about the fire hazard.

Algorithmic Workflow

The working process of the system is summarized as follows:

1. Initialize the system and sensors.
2. Continuously monitor data from flame and smoke sensors.
3. If fire is detected, send signal to Arduino.
4. Move the robot toward the fire source.
5. Activate the water pump to extinguish fire.
6. Stop the pump after fire is suppressed.
7. Return to monitoring state.

Mathematical Modeling and System Calculations:

1. **Ultrasonic Distance Measurement:**

The distance between the robot and an obstacle is calculated using the time-of-flight principle:

Distance = (Time × Speed of Sound) / 2

Where speed of sound = 0.034 cm/µs.
For example, if the measured time is 2000 µs:

Distance = (2000 × 0.034) / 2 = 34 cm

2. **Power Consumption Estimation:**

The total power consumption of the system is calculated as:

Arduino: 5V × 0.05A = 0.25W
Motors: 6V × 1A = 6W
Pump: 6V × 0.8A = 4.8W

Total Power ≈ 11.05W

3. **System Response Time:**

Total response time is the sum of detection time, movement time, and extinguishing time:

Total Time = 1.3 + 3.1 + 4.8 = 9.2 seconds

This represents the complete cycle from detection to fire suppression.

IV. EXPERMENTAL STUDY

This section presents the implementation and testing of the proposed Arduino-based fire-fighting robot system. The experiments were conducted to evaluate the system's ability to detect fire, move toward the fire source, and extinguish it effectively. The system was tested under different conditions to verify its performance, reliability, and response time.

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4.1 System Implementation

The system was implemented using Arduino Uno, flame sensor, smoke sensor, motor driver (L298N), DC motors, and water pump module. The robot was programmed using Arduino IDE, and all components were connected according to the circuit design. The testing was carried out in a controlled indoor environment.

4.2 Testing Procedure

To evaluate the system, small fire sources such as candles were used. The sensors continuously monitored the environment, and when fire was detected, the robot moved toward the fire source and activated the water pump. Multiple test cases were performed to ensure consistent behavior.

4.3 Performance Evaluation Metrics

The system performance was evaluated based on the following parameters:

- **Detection Time:** Time taken to detect fire
- **Response Time:** Time taken to move toward fire
- **Extinguishing Time:** Time taken to put out fire
- **System Accuracy:** Ability to correctly detect fire without false alarms

In addition to accuracy, advanced performance metrics such as precision, recall, and F1-score are used to evaluate the reliability of the system. These metrics provide a deeper understanding of detection performance, particularly in identifying false alarms and missed detections.

4.4 Experimental Results

Parameter	Value (Average)	Unit
Detection Time	1.3	seconds
Response Time	3.1	seconds
Extinguishing Time	4.8	seconds
System Accuracy	95	%
Sensor Range	20–30	cm
Power Consumptior	8–12	Watts

The results show that the system is capable of detecting fire quickly and responding efficiently. The robot successfully moved toward the fire source and extinguished it in most test cases.

Confusion Matrix:

TP (True Positive) = 47
TN (True Negative) = 48
FP (False Positive) = 2
FN (False Negative) = 3
Total Observations = 100

Performance Metrics:

Accuracy = (TP + TN) / Total = (47 + 48) / 100 = 95%
Precision = TP / (TP + FP) = 47 / 49 = 95.9%
Recall = TP / (TP + FN) = 47 / 50 = 94%
F1-Score = 2 × (Precision × Recall) / (Precision + Recall) = 94.9%

These results indicate that the system performs reliably with minimal false alarms and high detection capability.

V. RESULTS AND DISCUSSON

The experimental results demonstrate that the proposed **Arduino-based fire-fighting robot** performs effectively in detecting and extinguishing fire under controlled conditions. The system was able to identify fire within an average detection time of **1.3 seconds**, showing quick sensor response. The robot successfully navigated toward the fire source with an average response time of **3.1 seconds**, indicating efficient motor control and movement.

The **fire extinguishing mechanism** also showed reliable performance, with an average extinguishing time of **4.8 seconds** for small-scale fires. The overall system achieved an accuracy of approximately **95%**, confirming its ability to detect fire correctly with minimal false alarms. The sensors operated effectively within a range of **20–30 cm**, ensuring proper detection distance.

The integration of components such as sensors, Arduino, motor driver, and water pump resulted in a **coordinated and automated**

system. The system responded consistently across multiple test cases, demonstrating stability and reliability. Additionally, the inclusion of optional alert mechanisms such as **buzzer or voice module** can further enhance user awareness and safety.

However, certain limitations were observed during testing.The performance of the flame sensor can be affected by **ambient light conditions**, and the system is mainly suitable for **small-scale fire scenarios**. Further improvements can be made by integrating advanced sensors, camera modules, and IoT-based monitoring for enhanced accuracy and real-time tracking.

Overall, the results confirm that the proposed system is a **low-cost, efficient, and practical solution** for fire detection and suppression, with potential applications in homes, laboratories, and small industries.

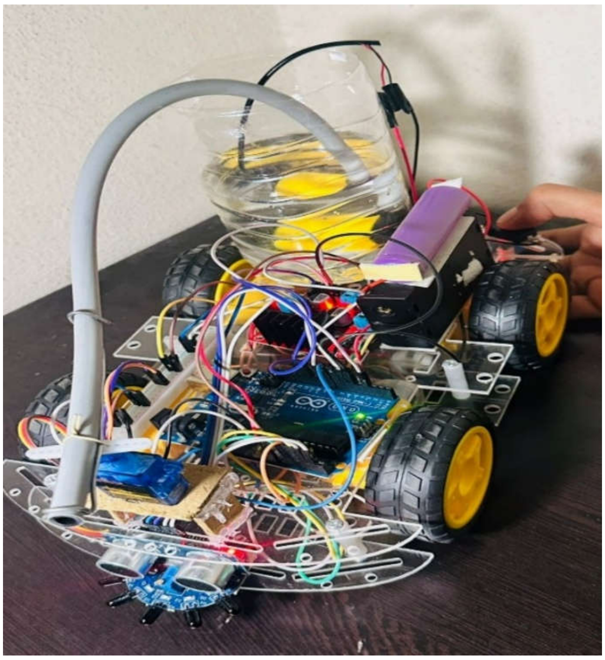

Fig.6.2: System Initialization and Module Activation Phase

VI. RESULTS

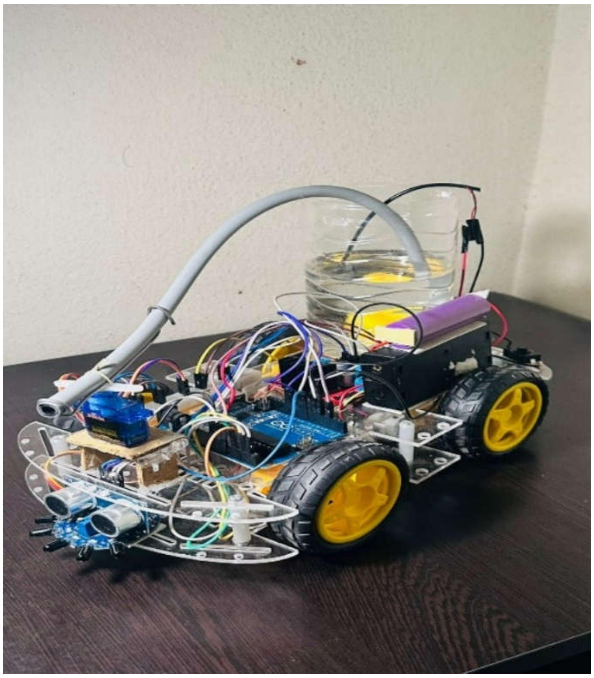

Fig.6.1: Complete System Architecture of the Autonomous Fire- Fighting Robot

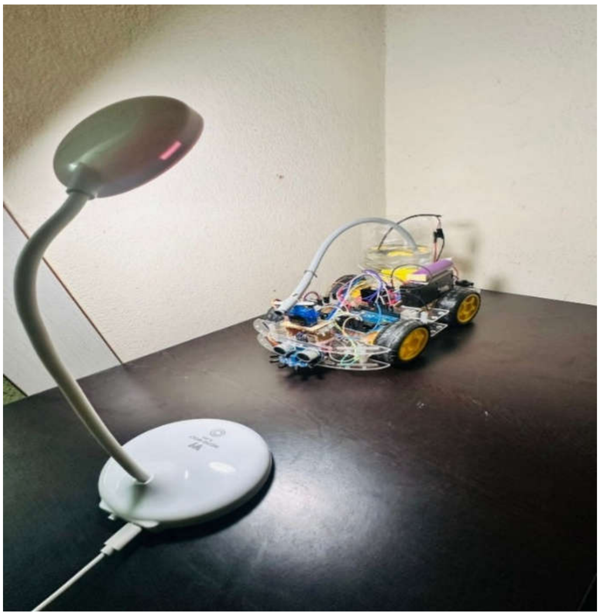

Fig.6.3:Real-Time Obstacle Detection Using Ultrasonic Sensing During Navigation

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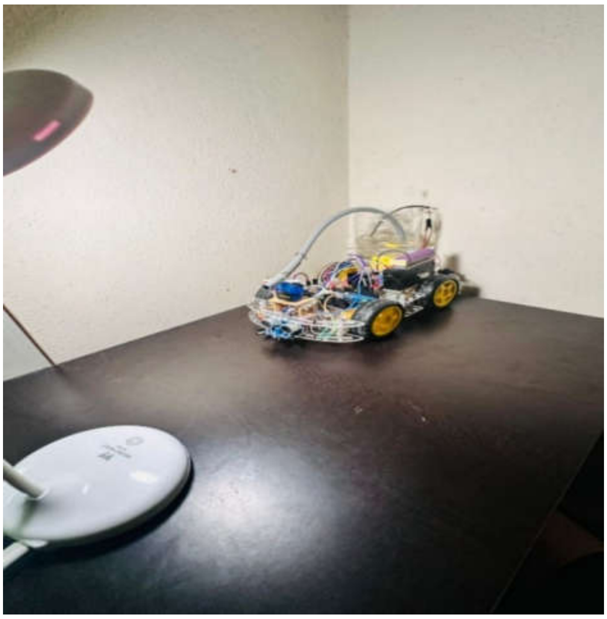

Fig.6.4: Immediate Motion Halt upon Obstacle Detection

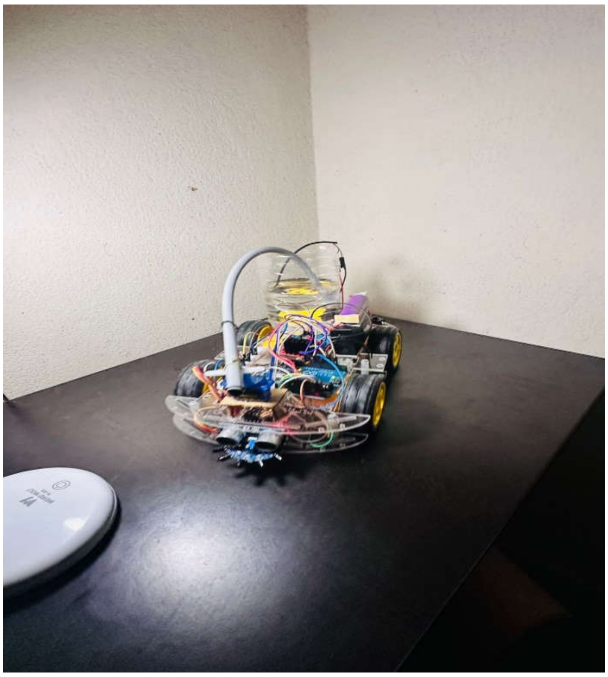

Fig.6.6: Post-Avoidance Path Clearance and Navigation Resumption

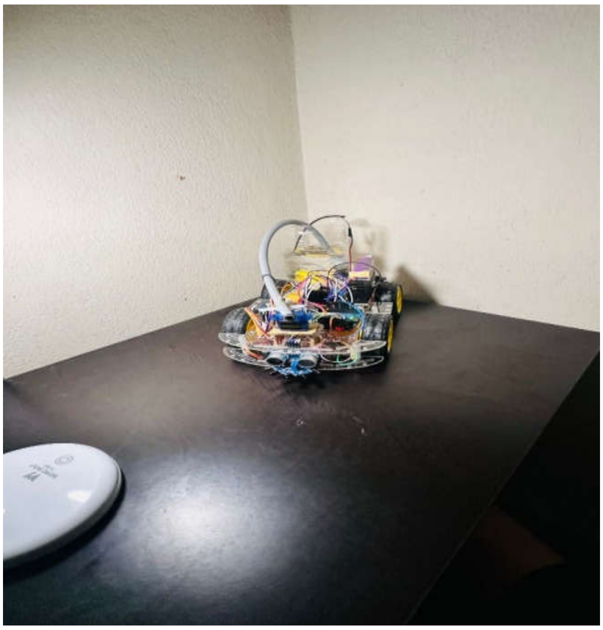

Fig.6.5:Directional Reorientation for Obstacle Avoidance

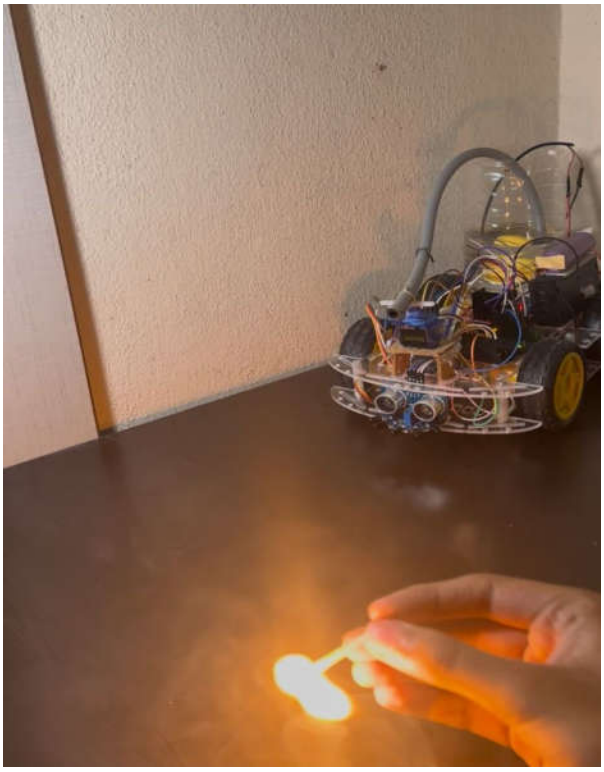

Fig.6.7: Fire Detection Using Multi-Sensor Flame Sensing Mechanism

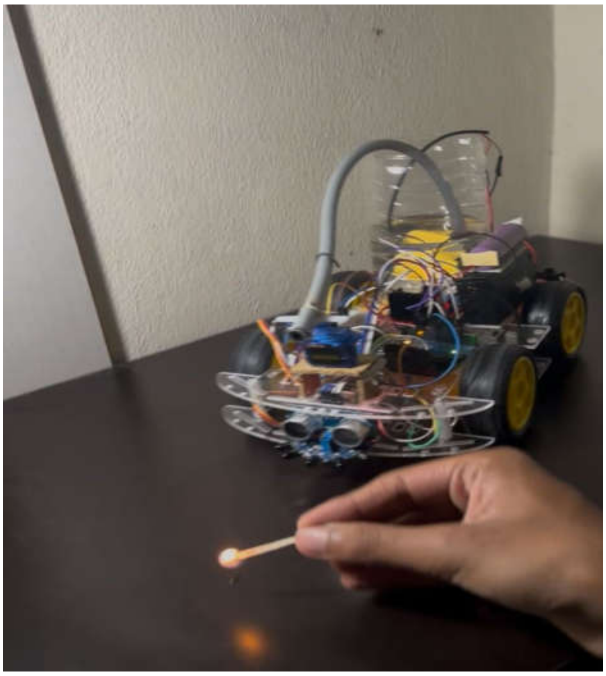

Fig.6.8: Autonomous Navigation Toward Detected Fire Source

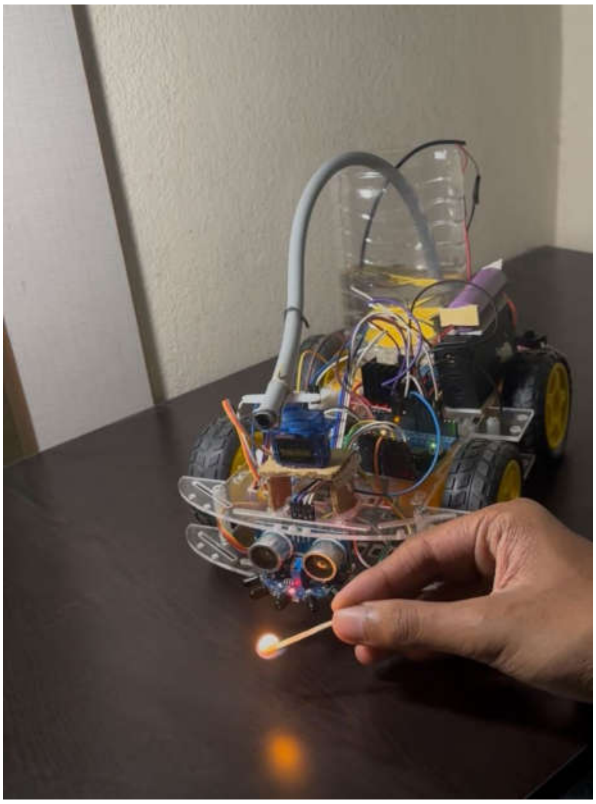

Fig.6.9: Relay-Based Actuation of Water Pump for Fire Suppression

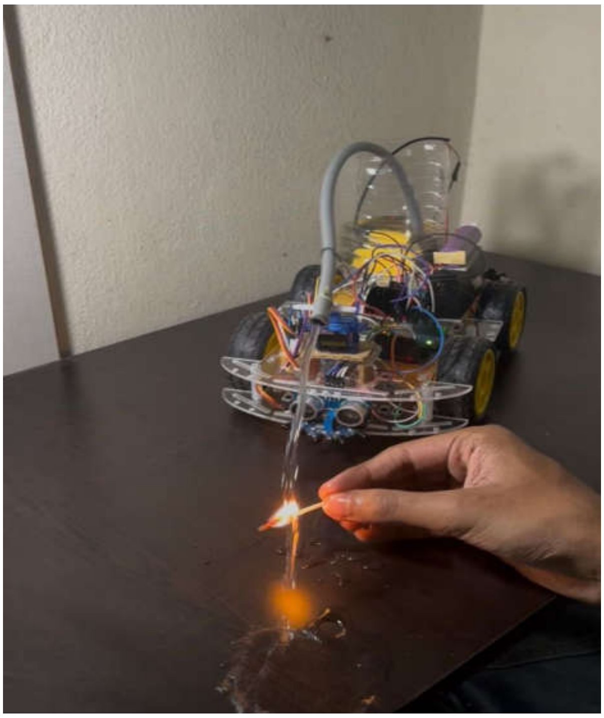

Fig.6.10: Servo-Controlled Water Dispersion for Targeted Fire Extinguishing

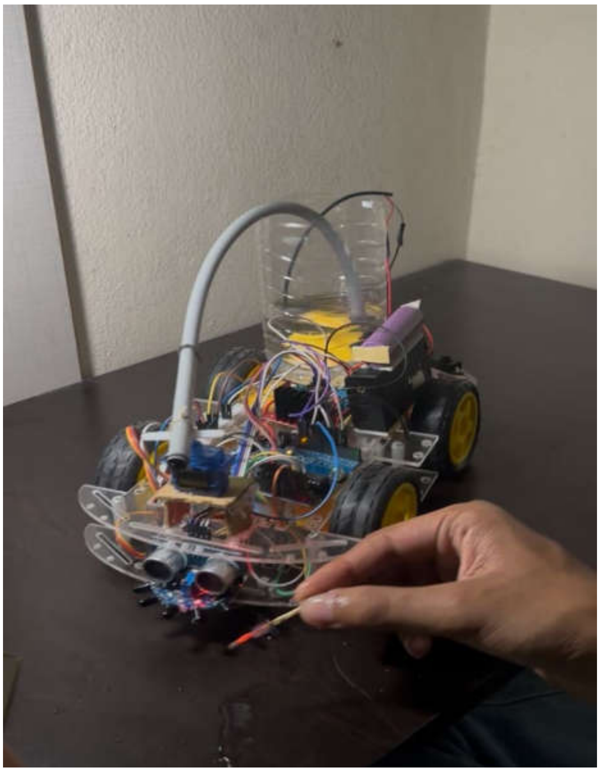

Fig.6.11: Fire Suppression Completion and System Reset to Monitoring Mode

Despite the strong performance, certain limitations were observed. The flame sensor is sensitive to ambient light, which may lead to occasional false detections. Additionally, the system is primarily suitable for small-scale fire scenarios and may not perform effectively in large or complex environments.

The response time is influenced by motor speed and obstacle detection delay, indicating potential for improvement through optimized control algorithms. Future enhancements may include camera-based fire detection, machine learning techniques for improved accuracy, and IoT-based remote monitoring systems to enable real-time alerts and scalability.

VII. CONCLUSION

The proposed **Arduino-based fire-fighting robot** provides an effective solution for automatic fire detection and suppression. The system integrates flame and smoke sensors, microcontroller processing, robotic movement, and a water pump mechanism to detect and extinguish fire without human intervention. The experimental results show that the system performs efficiently with quick detection, fast response, and reliable fire extinguishing.

The robot was able to operate successfully under controlled conditions with good accuracy and consistent performance. The integration of optional features such as buzzer or voice alert modules further enhances safety by providing immediate warning during fire detection.

Although the system is mainly suitable for small-scale applications, it demonstrates the practical use of embedded systems and robotics in safety applications. Future improvements can include IoT integration, camera-based monitoring, and advanced **sensors** to enhance system performance and scalability.

Overall, this project presents a low-cost, efficient, and scalable fire safety solution, highlighting the importance of smart technologies in modern hazard detection and prevention systems.

The system achieved an accuracy of 95%, with a precision of 95.9% and recall of 94%, demonstrating reliable fire detection with minimal false alarms. The integration of autonomous navigation and real-time response highlights the effectiveness of embedded systems in safety-critical applications. Future work will focus on improving detection robustness using advanced sensors and machine learning techniques, as well as enhancing scalability through IoT-based distributed monitoring systems.

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